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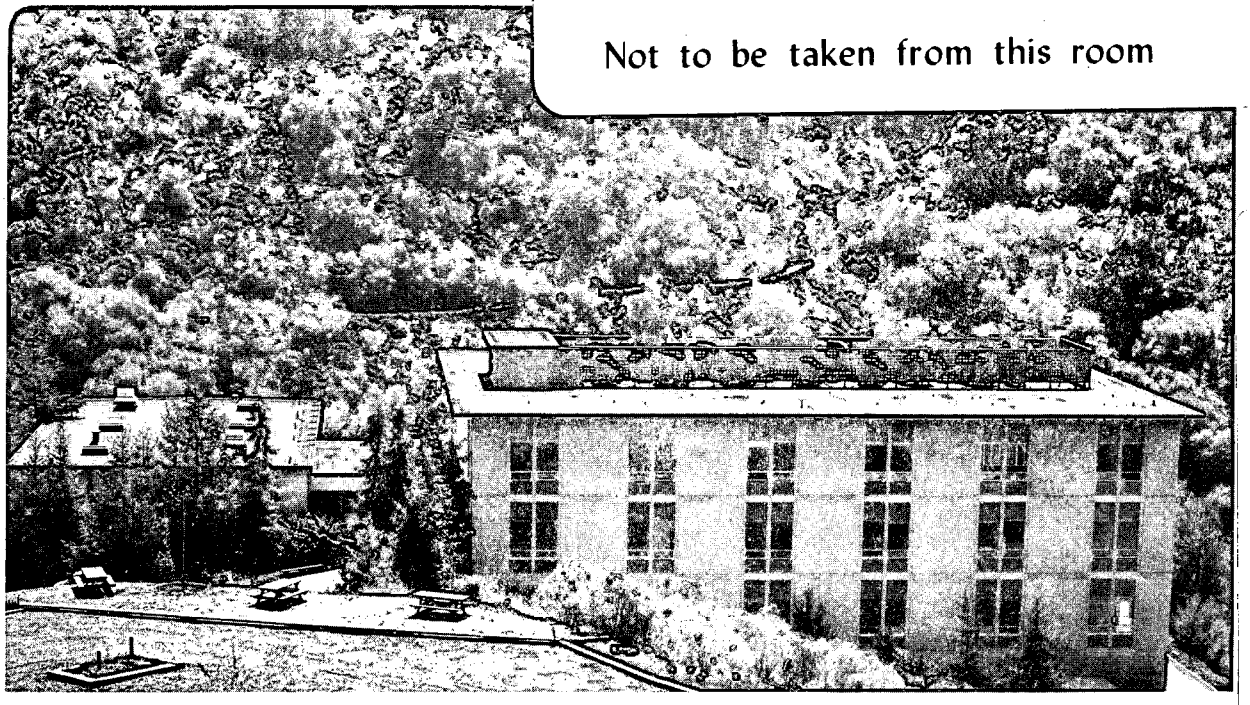

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## Abstract

The nature of the ultrafast response of the tunnel junction in a scanning tunneling microscope is discussed.

# Quantum Mechanical Capacitance in a Scanning Tunneling Microscope

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One of the most spectacular manifestations of quantum mechanics is tunneling between closely spaced conductors. The DC I-V characteristics in different types of tunnel junctions, such as metal-vacuum-metal junctions (MVM), metal-insulator-metal junctions (MIM), Josephson junctions, and quantum point contacts in a two dimensional electron gas, are well understood. High frequency transport in these systems is much less understood, and has been the subject of intense research in recent years[1,2].

The recently developed ultrafast scanning tunneling microscope (USTM) [3] is an ideal tool for the study of high frequency transport in the MVM or MIM system in a cross-sectional area on the order of 1 $nm^2$. In the USTM, an ultrafast photoconductive switch integrated with a scanning tunneling microscope (STM) tip assembly provides an ultrafast gate which temporally resolves the tunneling current. A "pump" laser pulse generates the surface excitation to be studied, and a "probe" laser pulse opens the sampling gate. An intriguing application of the USTM is the creation of movies of surface dynamics. At a fixed time delay between laser pulses, the tip can scan the surface, creating a snapshot of an ultrafast process. Such snapshots, viewed in succession, form a movie of surface dynamics. Before one can attempt to form movies, however, the USTM's response at a single point must be understood.

In what follows, we present experimental measurements of the high frequency response of the tunneling junction of a STM operating in air at room temperature. The tunnel junction is formed between the tip of the STM and the metallic surface of one strip of a coplanar transmission line on the sample. The STM tip position is fixed above a single point on the sample. A laser generates a picosecond voltage pulse on the transmission line, and the resulting tunnel current is monitored in time. The impedance of the tunneling gap can be deduced from the lineshape of the time-resolved tunnel current.

A typical signal measured by the USTM consists of a small AC component which varies with time delay and rides on a large DC background. The background is simply the DC tunneling current used for feedback, determined by the DC bias voltage and gap resistance. Fig 1a shows a 4.5 ps wide tunneling response to a 1 ps excitation pulse on the transmission line. The 10% to 90% rise time is 2 ps. The signal can also be measured while the tip is in ohmic contact, or crashed, with the sample. A typical crashed trace is shown in Fig. 1b. The time-resolved signal appears qualitatively different from the ohmic trace. In fact, the time-resolved signal's close resemblence to the derivative of the ohmic signal, shown in Fig. 1c., suggests that the tunnel junction has a partially capacitive response. However, the magnitude and the tip-sample separation dependence of this capacitive response are very different from that expected for the geometrical capacitance of the junction.

To better quantify the tunneling capacitance, we model the tunnel junction as a resistor, $R_t$, and a capacitor, $C_t$, in parallel. With the approximations: (1) that the RC discharge time of the circuit is smaller than the voltage pulsewidth, and (2). that the temporal width of the on cycle of the photoconductive switch is smaller than the voltage pulsewidth, we find that the time resolved signal is given by:

$$S(\tau) \propto S_{cr}(\tau) + T_t \cdot S_{cr}'(\tau) \qquad (1)$$

where $T_t = R_t C_t$ and $S_{cr}(\tau)$ is the crashed response. Eq. (1) states that the time resolved tunnel current can be fitted to $S_{cr}(\tau)$ and its derivative in time delay $S_{cr}'(\tau)$ with a single fitting parameter $T_t = R_t C_t$. This parameter has the dimensions of time delay, and is defined as the tunnel junction RC time constant. Since the tunneling gap resistance is known from DC measurements, we can extract the gap capacitance from the fitting parameter.

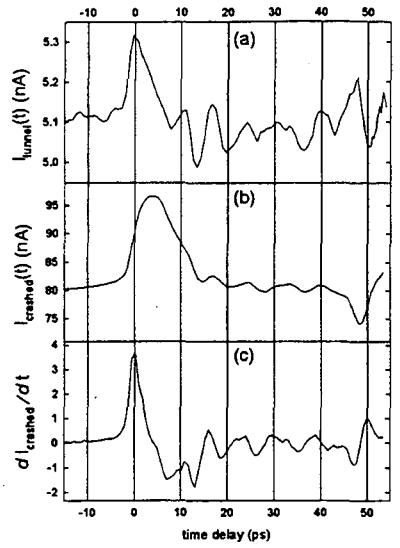


**Fig. 1.** Time resolved current cross-correlation detected on the tip: (a) in tunneling range (5nA and 80mV settings), and (b) when the tip is crashed into the sample. (c) is the time derivative of (b).

Fig. 2 is an example of such a fit. The solid line is the data of Fig. 1a. The fit (gray line) is obtained, according to Eq. (1), from the crashed signal data of Fig. 1b and its derivative in $\tau$. The tunneling capacitance extracted from the fit in Fig. 2 is $C_t = 6.7 \cdot 10^{-19}$ F. In a variety of measurements, we find $C_t$s varying from $10^{-19}$ to $10^{-21}$F. In contrast, the geometrical tip-sample capacitance is estimated to be larger than $10^{-15}$ F, even when the radius of curvature of the tip is as small as 1000 Å. The geometrical capacitance of the tip structure measured by conventional means at 20 kHz is $10^{-13}$ F.

The dependence of $C_t$ on tip-sample separation offers additional insight into the origin of this capacitance. This dependence is measured by retracting the tip and recording the time resolved tunnel current for different tip heights. In Fig. 3, we plot the extracted capacitance for three sets of measurements, each set taken with different combinations of tip and sample metallization or different excitation geometry, as a function of the tunneling gap conductance, $G_t$. We would prefer to plot $C_t$ as a function of the tip-sample separation, or barrier width, d.

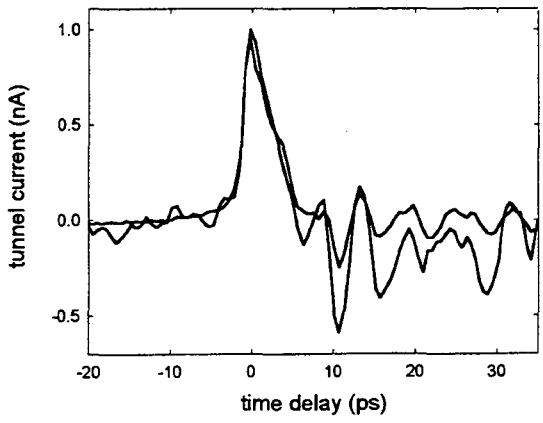


**Fig. 2:** Fit (solid gray line) to the time resolved data (solid black line) with the ohmic contact signal

However, in ambient conditions, the apparent inverse decay length and apparent barrier width is very different from a clean MVM junction, while the true inverse decay length is still represented by $G_t$. We find that the tunnel gap time constant, RC = $CG^{-1}$, depends only weakly on the barrier width. Since $G_t = G_0 e^{-\alpha(d-d_0)}$, where $\alpha$ is the inverse decay length, and $G_0$ is the conductance at a reference barrier width $d_0$ [4], the measured capacitance must vary as $C_t \propto e^{-\alpha(d-d_0)}$; in contrast, the geometrical capacitance can decrease no more rapidly than 1/d.

We conclude from the above discussion that (1) the time resolved tunnel current has a large capacitive component which originates from the tunneling itself, (2) the extracted capacitance is very small and is not the geometrical capacitance of the junction and (3) the capacitance varies exponentially with barrier width. Therefore, the capacitance has a quantum mechanical origin.

Experimental evidence of quantum reactance in the quasiparticle current in Josephson junctions [1] and in quantum point contacts in two dimensional electron gas systems [2] has been demonstrated only very recently. In both cases, the reactance is explained by the theory of photon assisted tunneling (PAT) [5] as originating from virtual transitions between the two electrodes of the junction. According to the PAT theory, the reactance can be derived from the DC I-V relation by a Kramers-Kroning (K-K) transformation. Since the DC response varies exponentially with tip height, a K-K transformation will preserve this exponential dependence, in accordance with experimental observations. Preliminary calculations indicate that the magnitude of the PAT capacitance is comparable to our results. An additional contribution to the quantum reactance can arise from the "electrochemical capacitance" [6] which originates from incomplete screening of the electric field in the metal.

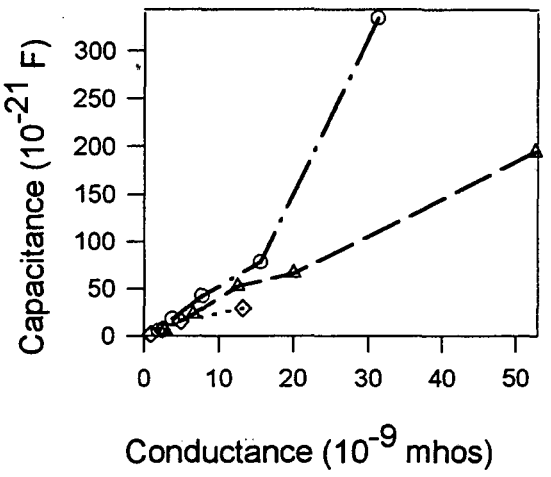


**Fig. 3** Junction capacitance vs. conductance. Data represented by circles taken with brass tip on Au sample. Data represented by diamonds or triangles taken with Pt-Rh tip on Al sample.

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